Preliminary investigation into the severe thunderstorm environment of Europe simulated by the Community Climate System Model 3

Patrick T. Marsh a,⁎, Harold E. Brooks b, David J. Karoly c

a University of Oklahoma, 120 David L. Boren Blvd, Norman, OK 73071, USA
b National Severe Storms Laboratory, 120 David L. Boren Blvd, Norman, OK 73071, USA
c School of Earth Sciences, University of Melbourne, VIC 3010, Australia

ARTICLE INFO

Article history:
Received 1 December 2007
Received in revised form 8 September 2008
Accepted 20 September 2008

Keywords:
Climatologies
Severe convection
Climate variability

ABSTRACT

Seasonal cycles of parameters conducive for the development of severe thunderstorms were computed using 20 years of output from the Community Climate System Model v3 (CCSM3) for both a 20th century simulation and a 21st century simulation. These parameters were compared against parameters calculated from the NCEP/NCAR Global Reanalysis data, which are of similar resolution. The CCSM3’s current simulation produced seasonal and spatial distributions of both mean CAPE and favorable severe environments that were qualitatively similar to the NCEP/NCAR Global Reanalysis, although the CCSM3 underestimates the frequency of severe thunderstorm environments. Preliminary comparisons of the CCSM3’s 21st century simulation under the IPCC’s A2 emissions scenario to the 20th century simulation indicated a slight increase in mean CAPE in the cool season and a slight decrease in the warm season and little change in mean wind shear. However, there was a small increase in favorable severe environments for most locations resulting from an increase in the joint occurrence of high CAPE and high deep layer shear. Regions near the Mediterranean Sea experienced the biggest increase in both mean CAPE and favorable severe environments, regions near the Faeroe Islands experienced an increase in only seasonal mean CAPE, and regions across northern Europe experienced little change.

© 2008 Elsevier B.V. All rights reserved.

1. Introduction

The American Meteorological Society’s glossary defines climate change as any discernable change in any aspect of the present climate, such as temperature, moisture content, or precipitation, persisting on time scale of at least a decade (AMS, 2008). These changes can occur from a variety of means including, but not limited to, changes in anthropogenic forcing (greenhouse gasses and aerosols in the atmosphere) and solar activity. The Intergovernmental Panel on Climate Change (IPCC, 2007) has stated that global-average temperature increases over the past 50 years are most likely the result of anthropogenic activities and projects an increase in future mean temperature. However, the IPCC (2001) stated that, “Although of great importance to society for their potential for causing destruction, as well as their human and economic impacts, there is little guidance from AOGCMs concerning the future behavior of tornadoes, hail or lightning” (Cubasch et al., 2001).

Figure SPM5 of the IPCC’s Fourth Assessment Report’s Summary for Policy Makers (available: http://www.ipcc.ch/graphics/graphics/ar4-wg1/jpg/spm5.jpg) displays the projected increase in temperature through 2100 derived from a suite of ensembles used by the IPCC in their Fourth Assessment Report. From this figure, it is readily apparent that all models for all emission scenarios show an increase in mean temperature by the end of the 21st century. An increase in the mean temperature results in more hot weather than cold weather when compared to the initial mean temperature. While it is clear that the increase in mean temperature
will result in more hot weather, it is not clear what will happen to other atmospheric variables that are more directly relevant to thunderstorms, such as Convective Available Potential Energy (CAPE) and wind shear. Possible impacts of an increasing mean temperature include the ability of the atmosphere to hold more moisture leading to an increase in CAPE and subsequently stronger convection. Another possibility is the increase of middle to upper tropospheric temperatures, which would lead to an increase in static stability, a decrease in CAPE, and, in turn, weaker convection.

Before making predictions about potential impacts of global warming on severe convective weather, climatologies of current severe convective weather must be constructed and analyzed. Assessing climatologies of actual observed severe convective weather events is a difficult task because of the very small spatial and short temporal resolution at which these phenomena occur. When inconsistencies in reporting criteria and improvements in the technology used to observe severe convective weather events are taken into account, the problem of developing reliable long-term climatologies becomes nearly impossible (Doswell et al., 2005; Brooks and Doswell, 2001).

In an attempt to minimize the difficulties of working with atmospheric events that are not reported consistently, Brown and Murphy (1996) proposed the use of covariates that represent the atmospheric event’s environment as proxies for the occurrence of the event itself. In an attempt to formulate climatologies of severe convective weather, Brooks et al. (2003) examined several environmental parameters previously shown to be conducive for the development of severe convective weather. These parameters included, but were not limited to, CAPE, magnitude of the vector difference between the surface and six kilometer wind (hereafter referred to as deep layer shear), and product of CAPE and deep layer shear. In both the Brown and Murphy study and the Brooks et al. study, extreme values of the covariates were closely related to the average occurrence of the atmospheric event being proxied. Thus, in the context of establishing climatologies of severe convective weather events, the problem is transformed from trying to assess an inherently inadequate database of observed severe convective weather events to trying to establish a relationship between better-observed environmental conditions and the original events in question.

Observed environmental parameters derived from meteorological soundings near severe convective weather events demonstrate that as CAPE and deep layer shear increases the probability of severe convective weather events also increases (Rasmussen and Blanchard, 1998). Convective parameters derived from the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) global reanalysis (hereafter referred to as simply reanalysis; Kalnay et al., 1996) have been shown to be qualitatively similar to convective parameters derived from observed soundings (Lee, 2002). Using reanalysis output, Brooks et al. (2003) calculated CAPE – from a parcel mixed parcel over the lowest 100 hPa above the surface – as well as deep layer shear. Their results were consistent with those of Rasmussen and Blanchard. Furthermore, CAPE calculated from reanalysis output showed a strong relationship to hail incidents (Niall and Walsh, 2005). However, one caveat mentioned by Brooks et al. (2003) is that the difference between tornadic environments and severe but non-tornadic environments is harder to differentiate in the reanalysis output than observational data.

Continuing previous work, Brooks et al. (2007) explored the annual cycle of severe convective weather environments from the reanalysis. It was found that the reanalysis output qualitatively captures the spatial and temporal variability of severe convective weather environments observed in the United States (Brooks et al., 2003; Doswell et al., 2005). Brooks et al. (2003) concluded that the central part of the United States was the region with the most frequent number of days with favorable severe convective weather environments. This ability of the reanalysis to qualitatively recreate severe convective weather environments points toward the possibility that atmospheric models of similar resolution might be capable of doing the same. Marsh et al. (2007) demonstrated that NCAR’s Community Climate Systems Model v3 (CCSM3) is capable of representing the severe convective weather environment, at least qualitatively, for North America.

2. Datasets

2.1. Reanalysis dataset

Atmospheric variables computed from the reanalysis were provided by Brooks et al. (2003). A detailed explanation of how the necessary atmospheric variables from the reanalysis were calculated can be found there. The CAPE and deep layer shear fields were computed using a version of the Skew-t/Hodograph Analysis and Research Program (SHARP). It is important to note that the CAPE calculated from SHARP was computed from a parcel with potential temperature and moisture mixed over the lowest 100 hPa above the surface (Brooks et al., 2003).

2.2. CCSM3 dataset

The CCSM3 is a coupled global climate model consisting of atmosphere, land surface, sea-ice, and ocean components (Collins et al., 2006) developed at NCAR. Each component is a model in itself joined together through a flux coupler and each component only exchanges information with the flux coupler. There is no direct interaction between components. In general, any flux field is computed in one component on that component’s model grid and is then made available to the other components via the flux coupler for use as boundary forcing information.

The atmospheric portion of the CCSM3, the Community Atmospheric Model 3 (CAM3), is a spectral model with 85-wavenumber triangular truncation (approximately 1.4° at the equator) in the horizontal with 26 terrain-following hybrid levels in the vertical. The numerical scheme used in the CAM3 is an Eulerian spectral transform with semi-Lagrangian tracer transport and semi-implicit leapfrog time stepping (Collins et al., 2006). CAM3’s vertical resolution contains 4 levels below 850 hPa and 13 levels above 200 hPa (topmost being 2.2 hPa).

The land-surface portion of the CCSM3, the Community Land Model 3 (CLM3) uses a horizontal resolution identical to that of the CAM3 (Vertenstein et al., 2004) and 10 levels (soil layers in the vertical (Oleson et al., 2004). The oceanic portion
2.3. Calculation of atmospheric variables from CCSM3

The CCSM3 archived output does not include a CAPE or deep layer shear field and thus had to be computed from the available output. The calculation of CAPE was done using the NCAR Command Language (NCL), specifically the rip_cape routines; there are two versions of the rip_cape routine: rip_cape_2d and rip_cape_3d. Both of these routines take arrays of pressure, temperature, geopotential height, mixing ratios, surface pressure and surface geopotential. It is important to note that both of the rip_cape routines compute CAPE using the model output’s vertical grid and is not interpolated.

The difference between the two CAPE routines is the “parcel” used to compute the positive buoyancy. In the rip_cape_2d routine, the term “parcel” refers to a 500-meter thick layer centered on the grid level with the maximum equivalent potential temperature with potential temperature and mixing ratio averaged throughout the layer. In the rip_cape_3d routine, the term parcel “refers” to a 500-meter layer centered on any grid point with potential temperature and mixing ratio averaged throughout the layer. The rip_cape_3d routine then returns an array containing CAPE values at all horizontal and vertical grid points. Neither of these methods is equivalent to the method used by Brooks et al. (2003), however using the model layer closest to the surface from the rip_cape_3d routine provided the most similar parcel. Because the CCSM3 parcel is mixed over 500-m, the temperature and moisture content of the CCSM3 parcel is greater than the temperature and moisture content of the reanalysis parcel which is mixed over a deeper depth. Thus, the CCSM3 parcel would yield higher CAPE than the reanalysis parcel, given the same environment.

Archived CCSM3 output includes the U and V components of the wind. Once again, this output is stored on the model’s hybrid levels — not in physical height coordinates. Thus, to calculate the deep layer shear, the output was converted from hybrid levels to geopotential height using built in routines of NCL. Since the six-kilometer wind was seldom located on one of the model’s twenty-six vertical levels, a linear interpolation routine in NCL was used to interpolate the U and V wind components to a height of 6 km above ground level. In an effort to reduce necessary computations, instead of using the ten meter wind (which would require extrapolation), the U and V components of the model layer closest to the surface were used as the surface winds component.

2.4. Analysis of the CCSM3 severe convective weather environment

As previously mentioned, Brook et al. (2003) demonstrated the effectiveness of using environmental covariates derived from the reanalysis dataset in assessing the observed severe convective weather environment. Essentially, this was done by mimicking the traditional proximity sounding methodology, i.e., comparing derived convective parameters from the reanalysis fields to observed severe convective weather environments. Building on this success, an analysis of the severe convective weather environment of the CCSM3 will be carried out in a similar manner.

The reanalysis dataset is derived from real observations made every 6 h and therefore should have some semblance of reality. For example, reanalysis data for 21 July 1983 should correspond to observational data for 21 July 1983. This same relation between observations for a specific date and the...
reanalysis does not hold for observations and global climate model output, including the CCSM3.

The 20th century runs of the CCSM3 were initialized in 1870 and while changed in anthropogenic forcing corresponding to observations are updated every model year, the fact still remains that the initial conditions for the model run were based on conditions in 1870. This means that there is no resemblance of specific model day 21 July 1983 to observed day 21 July 1983 — apart from the general external radiative forcing conditions for that date such as solar irradiance, GHGs, and sulphate and volcanic aerosols. This is a critical distinction to make as it means the analysis of CCSM3 output cannot be carried out in the exact manner the analysis of the reanalysis dataset was performed. Namely, any semblances observations of severe convective weather on a given (observed) day to the same day in the CCSM3 runs are strictly coincidental.

Since a direct comparison of CCSM3 model years to observed years cannot be made, a fundamental question must be asked. Given that there is no 21 July 1983 in the model, how does one determine if the model environments are representative of actual environments? In an effort to assess the model severe convective weather environment, analyses were carried out in a variety of ways and on multiple temporal scales. This included comparisons of the model output with reanalysis output over the European domain in yearly, seasonal, and decadal time scales. CAPE was investigated in both its own dimension as well as in joint distributions of CAPE and deep layer shear. If the statistics of the CCSM3 model severe convective weather environments are qualitatively similar to the statistics of the reanalysis environments, then it can be said that the model produces reasonable severe convective weather environments.

**Fig. 1.** Spatial distribution of mean CAPE for (a) December through February from reanalysis, (b) March through May from reanalysis, (c) June through August from reanalysis, (d) September through November from reanalysis, (e) December through February from 20th century simulation, (f) March through May from 20th century simulation, (g) June through August from 20th century simulation, and (h) September through November from 20th century simulation. CAPE values of 0 were included in these calculations.
The analysis of the future severe weather environment as simulated by the CCSM3 was conducted in a similar manner as that stated above for the current simulation. The difference is that comparisons will be made between the simulated future severe weather environment and the simulated current severe weather environment—not between model and reanalysis.

It cannot be stressed enough that it is not necessary to get the absolute magnitudes of CAPE and deep layer shear correct when compared to the reanalysis output for the analysis to provide useful information. Therefore, the analysis is biased towards comparisons of relative terms.

### 3. Results

#### 3.1. Results from CCSM3 20th century simulation

Mean CAPE values computed from the CCSM3 were qualitatively similar to mean CAPE values computed from the reanalysis\(^1\) (Fig. 1). During the winter months (December through February) mean CAPE values computed from the CCSM3's 20th century simulation (hereafter current simulation) captured a lack of CAPE across most of the European region, with mean CAPE greater than 20 J kg\(^{-1}\) only found in the northeastern Atlantic Ocean and the eastern two-thirds of the Mediterranean Sea. A seasonal maximum existed to the northwest of Scotland, where a small region of mean CAPE values greater than 60 J kg\(^{-1}\) was found.

The spring months (March through May) had a slight increase in mean CAPE values from less than 20 J kg\(^{-1}\) to greater than 20 J kg\(^{-1}\) across the northwestern half of France, Belgium, portions of Germany, central Poland, southern Belarus, and northern Ukraine. Areas bordering the east coast of the Black Sea also showed an increase in mean CAPE values to above 20 J kg\(^{-1}\). The highest mean CAPE values across southern Europe were found near the central Mediterranean Sea; a slight decrease was found across the eastern Mediterranean Sea. Mean CAPE values also decreased across the northeastern Atlantic Ocean with the most noticeable decreases off the west coast of Portugal.

By the summer months (June through August), most of the far northeastern Atlantic Ocean had mean CAPE values less than 20 J kg\(^{-1}\). The exception to this decreasing trend was found across the Faeroe Islands region and along the southeastern coasts of Portugal and Spain, with the latter region having a fairly large increase. Almost all of mainland Europe had mean CAPE values greater than 20 J kg\(^{-1}\) with a majority having mean values greater than 40 J kg\(^{-1}\). The highest mean CAPE values were found over the Mediterranean Sea—on either side of the Strait of Gibraltar—and south of Italy and Greece. In these regions mean CAPE values were well over 100 J kg\(^{-1}\). The highest mean CAPE values across mainland Europe were found across southwestern Spain (~80 to 100 J kg\(^{-1}\)) and in a west to east oriented zone stretching from central Germany, across Czech Republic and central Poland, along the borders of Belarus and Ukraine ending in far western Russia (60–80 J kg\(^{-1}\)).

---

\(^1\) It is important to reiterate that the mean values computed from the CCSM3 are 20 year means taken from the last twenty years of the model run. The mean values computed from the reanalysis are 42 years means taken from 1958 to 1999.
Mean CAPE values for the autumnal months (September through November) decreased across almost the entire region. All of central and eastern mainland Europe decreased, where mean values were less than 20 J kg\(^{-1}\); however, two regions appeared to show a slight increase in mean CAPE, namely, the southwest coast of Italy and the region surrounding the Faeroe Islands. An interesting observation was that mean CAPE values over large bodies of water (e.g., Mediterranean Sea, Black Sea, and Caspian Sea) had a smaller decrease than regions of land.

Quantitative comparisons of CCSM3 mean CAPE to reanalysis mean CAPE revealed large deficiencies in the CCSM3. This was not completely unexpected as the CCSM3’s deep convection parameterization scheme is designed to destroy CAPE as soon as it is large enough to penetrate the model’s stable layer. This quick destruction of CAPE prevents the buildup of large values which would impact seasonal means. The reanalysis does not have a deep convection parameterization scheme and thus large CAPE values can build up. Even though the deep convection parameterization of the CCSM3 affects the quantitative results, the parameterization should not have an effect on spatial distribution.

A qualitative comparison of the seasonal cycles showed a similar signal between the CCSM3 and reanalysis. Both datasets had low mean CAPE values over most of mainland Europe during the winter months, with slightly higher values over the northeastern Atlantic Ocean and Mediterranean Sea. In the months of spring, both datasets began to increase mean CAPE values over mainland Europe and east of the Black Sea, while decreasing the magnitude and spatial extent of mean CAPE values over the Atlantic Ocean and Mediterranean Sea. The summer months continued the trend of increasing mean CAPE values over mainland Europe and decreasing mean CAPE values over the Atlantic Ocean. One important difference between the CCSM3 and reanalysis was the location of the maxima; the CCSM3 had mean CAPE maxima over portions of the Mediterranean Sea, while the reanalysis had maxima over mainland Europe. By the autumnal months, mean CAPE values had decreased by large amounts over mainland Europe and the Mediterranean Sea. A seasonal maximum could be found in the central Mediterranean Sea and mean CAPE values began increasing over the northeastern Atlantic Ocean.

One complication in using datasets of different temporal, and in this case spatial, resolution is that direct comparisons of distributions are non-trivial. In an attempt to accurately compare the joint distribution of CAPE and deep layer shear between the 20 year CCSM3 dataset and the 42 year reanalysis dataset the following normalization technique was used.

1. Count the number of occurrences of the joint CAPE and deep layer shear values in specific ranges for all 6 hour time periods at all gridpoints in the domain.
2. Divide the resulting value by the number of gridpoints in the domain.
3. Divide the resulting value by the number of years contained in the time period of the respective dataset.

Normalization by this technique yielded the mean annual joint distribution of CAPE and deep layer shear for a representative gridpoint within the domain, allowing for direct comparison between the two datasets.

The current simulation’s normalized frequency distribution (in log–log space) showed a peak occurrence of about six occurrences centered near CAPE and deep layer shear combinations of 50 J kg\(^{-1}\) and 20 m s\(^{-1}\) (Fig. 2). Moving out from this maximum in occurrence, frequency of
occurrence decreased rapidly in environments with higher CAPE and higher deep layer shear as well as environments with lower CAPE and lower deep layer shear. The decrease in occurrence was more gradual when CAPE was held nearly constant and deep layer shear was decreased and even less when CAPE was decreased and deep layer shear was held constant. Most of the environments occurred when deep layer shear was between 5 and 20 m s$^{-1}$.

The normalized frequency distribution from the reanalysis (in log–log space as well) had a maximum in occurrence when CAPE was near 30 J kg$^{-1}$ and deep layer shear was slightly less than 20 m s$^{-1}$ (Fig. 3). Similar to the CCSM3’s distribution, the number of occurrences of environments gradually decreased when deep layer shear was held nearly constant and CAPE was decreased. Similar to the CCSM3, most of the occurrences are found in a range of 5 to 20 m s$^{-1}$. On the whole, it appeared that the CCSM3’s maximum occurrence favored environments with slightly higher CAPE than the reanalysis, however, the reanalysis more frequently achieved higher CAPE values than the CCSM3.

Through the use of linear discriminant analysis, Brooks et al. (2003) computed a “best” discriminator line (hereafter BLC03 discriminant) between significant severe and severe convective weather. Inspection indicates that this discriminant can be approximated as the product of CAPE and deep layer shear equal to 10,000 m$^3$ s$^{-3}$. Using the modified BLC03 discriminant, environments where the product of CAPE and deep layer shear are greater than or equal to 10,000 m$^3$ s$^{-3}$ can be thought of as favorable for the development of severe convective weather assuming the environment is realized by convection.

The annual count of six hour periods with environments favorable for the development of severe convective weather (hereafter referred to as favorable severe environments)
computed from the CCSM3 indicated a strong model preference for regions near warm water. Breaking this down into seasons (Fig. 4), the current simulation produced less than 5 periods of favorable severe environments for December through February and March through May. From June through August, most of mainland Europe and the Mediterranean Sea had at least 5 periods with favorable severe environments, with central Poland, southern Belarus, and northern Ukraine having over 10 periods of favorable severe environments. The western Mediterranean Sea had the most periods of favorable severe environments, maxing out near the Strait of Gibraltar with over 40 periods. By September through October, most of the European region had decreased back to less than 5 periods of favorable severe environments. The exception to this was over the Mediterranean Sea, where nearly the entire sea had at least 5 periods, and southeast of Italy had over 20.

The reanalysis had the similar void of regions with greater than 5 periods of favorable severe environments from December through February as the CCSM (Fig. 4). However, by March through May, the reanalysis had a region with greater than 5 periods, increasing to greater than 20 periods over the eastern Black Sea and areas to the southeast. For the same time frame, the CCSM3 still had no region with greater than 5 periods. During June through August, the reanalysis had several maxima over the European region including northwestern Spain and southwestern France (between 20 and 30 periods), northern Italy (between 20 and 25 periods), and east of the Black Sea (with between 15 and 25 periods). This compared to significantly fewer periods in the CCSM3 however the general shape to the spatial distribution of regions with greater than 5 periods appeared to be similar. By the months of September through November the reana-

Fig. 5. Spatial distribution of mean CAPE for (a) December through February from 20th century simulation, (b) March through May from 20th century simulation, (c) June through August from 20th century simulation, (d) September through November from 20th century simulation, (e) December through February from 21st century simulation, (f) March through May from 21st century simulation, (g) June through August from 21st century simulation, and (h) September through November from 21st century simulation. CAPE values of 0 were included in these calculations.
Lysis did not have more than 5 periods of favorable severe environments across all of mainland Europe, with the exception of the coastal regions of southeastern Spain and southern Italy, where between 5 and 10 periods occurred. Spatially, this matched reasonably well with the CCSM3, however the CCSM3 had more periods with favorable severe environments.

3.2. Results from CCSM3 21st century simulation

The CCSM3’s simulation of the 21st century (based on the A2 emissions scenario) had small to zero mean CAPE values over much of mainland Europe during the winter months (Fig. 5). Coastal regions of mainland Europe had slightly higher values, but were still less than 40 J kg\(^{-1}\). Slightly higher mean CAPE values were found west of the Strait of Gibraltar, south of Italy, and to the west of Norway, with each region having peak mean values of greater than 60 J kg\(^{-1}\).

Mean CAPE values for the months of spring had decreased across much, if not all, of the European region. Most of mainland Europe had mean CAPE values of less than 20 J kg\(^{-1}\), with two exceptions: extreme southern Italy and extreme northwest Spain through northwest France, where values of between 20 and 40 J kg\(^{-1}\) were found. North of the British Isles a maximum in mean CAPE values occurred with peak values greater than 60 J kg\(^{-1}\).

During the summer months, mean CAPE values increased over most of mainland Europe and the waters of the Mediterranean Sea. The highest values were found southeast of Italy and southwest of Greece where values over 80 J kg\(^{-1}\) were found. Other local maxima occurred west of the Strait of Gibraltar (between 60 and 80 J kg\(^{-1}\)), the southern Black Sea (between 40 and 60 J kg\(^{-1}\)), and the eastern portions of Belarus and the Ukraine (40 to 60 J kg\(^{-1}\)). The region surrounding the Faeroe Islands experienced a decrease in mean CAPE as did most locations in the northeast Atlantic Ocean.

The autumnal months had a large increase in mean CAPE values across the Mediterranean Sea and just west of the Strait of Gibraltar. The rest of the European region had little change. A slight decrease in the magnitude and spatial extent of the highest mean values and a slight increase in the spatial extend of the lowest mean values being the only changes.

When compared to the CCSM3’s 20th century simulation (hereafter referred to as the current simulation), several changes to the seasonal distribution of mean CAPE became apparent in the 21st century simulation (hereafter referred to as the future simulation). The winter months’ mean CAPE values had increased across much of the Mediterranean Sea and the areas near the Strait of Gibraltar. The latter region had a mean CAPE increase from less than 20 J kg\(^{-1}\) in the current simulation to over 60 J kg\(^{-1}\) in the future simulation. Other areas with increases included the region around the Balearic Islands (from ~20 J kg\(^{-1}\) to over 40 J kg\(^{-1}\)), south of Italy (from ~20 J kg\(^{-1}\) to over 60 J kg\(^{-1}\)), and southern portions of the Black Sea (from <20 J kg\(^{-1}\) to ~20 J kg\(^{-1}\)). The region surrounding the Faeroe Islands had the maximum mean CAPE values shift eastward closer to the west coast of Norway.

For the entire European region, the spring months had a decrease in mean CAPE values in the future simulation. The few areas across mainland Europe where mean CAPE

![Fig. 6. Difference between the joint distribution of CAPE and deep layer shear calculated from the 21st century simulation and the 20th century simulation. Increases in the 21st century simulation are shaded while decreases are contoured (dashed). The solid, black line in the upper right portion of the figure is the modified BLC03 discriminant (product of CAPE and deep layer shear greater than 10,000 m\(^3\) s\(^{-3}\)). Environments above and to the right of this threshold are the differences in environments considered favorable for severe thunderstorms.](image-url)
values were greater than 20 J kg$^{-1}$ in the current simulation had almost all decreased to less than 20 J kg$^{-1}$ in the future simulation. The spatial coverage of mean CAPE values greater than 20 J kg$^{-1}$ decreased across the central Mediterranean to only include small regions south of Italy and east of Crete. The only increase occurred in the region near the Faeroe Islands where both the spatial coverage and peak values increased slightly. Comparisons of the current and future simulations’ summer months captured an almost complete decrease in mean CAPE everywhere across the European region. The only exception was found off the west coast of Norway where values were slightly increased. Comparisons of the autumnal months had an increase in mean CAPE values across most of the Mediterranean Sea region along with mainland Europe, while the northeast Atlantic Ocean and the Faeroe Island region had a decrease in mean CAPE values.

Examination of the future simulation’s annual joint CAPE-deep layer shear distribution revealed a distribution similar to the current simulation’s distribution. In the current simulation the center of this maximum region appeared to be located near CAPE of 50 J kg$^{-1}$ and deep layer shear near 20 m s$^{-1}$. In the future simulation, this maximum appeared to be centered on an environment with CAPE of 50 J kg$^{-1}$ and deep layer shear around 15 m s$^{-1}$. At first glance, the only difference between the future and current simulations appeared to be a slight increase in the distribution toward the higher CAPE values. However, a difference plot between the future and current simulations was constructed (Fig. 6) and revealed that the number of environments in low CAPE, high deep layer shear regions actually decreased by up to 1.5 periods. The greatest increase in occurrence was in the high CAPE and low deep layer shear region. It is worth noting that a secondary

\[ \text{Number of Favorable Severe Periods By Season} \]

\[ \text{20th Century Simulation} \quad \text{21st Century Simulation} \]

![Fig. 7. Spatial distribution of the number of environments favorable for severe thunderstorms for (a) December through February from 20th century simulation, (b) March through May from 20th century simulation, (c) June through August from 20th century simulation, (d) September through November from 20th century simulation, (e) December through February from 21st century simulation, (f) March through May from 21st century simulation, (g) June through August from 21st century simulation, and (h) September through November from 21st century simulation. CAPE values of 0 were included in these calculations.} \]
maximum in increase occurred at relatively large CAPE (1000 J kg^{-1}) and low deep layer shear (10 m s^{-1}).

Using the modified BLC03 discriminant of the product of CAPE and deep layer shear greater than 10,000 m^3 s^{-3}, annual counts of six hour periods with favorable severe environments for the future simulation were constructed (Fig. 7). The three month periods of December through February and March through May both had less than 5 periods of favorable severe environments. By June through August most of mainland Europe had greater than 5 periods of favorable severe with a large swath of greater than 10 periods from Switzerland to Poland to Russia. A second region of greater than 10 periods is found near large areas of warm water (e.g., Mediterranean Sea, Black Sea, and Caspian Sea). The maximum number of periods for this time frame was found of the Mediterranean coast of Spain where greater than 40 periods of favorable severe environments occurred. During September through November, regions with greater than 5 periods of favorable severe were limited to near the Mediterranean Sea, Black Sea, and Caspian Sea.

The seasonal distribution of the number of favorable severe environments was qualitatively similar between the current and future simulation. December through February and March through May had less than 5 periods favorable for severe in both simulations. June through August had a slight increase in occurrence across most of mainland Europe and a large increase over regions of warm water. By September through November, the spatial distributions were once again similar between simulations, with the future simulation having more favorable severe environments than the current simulation near regions of warm water.

4. Discussion

Qualitatively, the CCSM3 showed promise as a global climate model capable of representing severe thunderstorm environments over Europe. The CCSM3 qualitatively captured the correct seasonal cycle of mean CAPE and favorable severe environments as represented by the reanalysis. Furthermore, the CCSM3 current simulation and the reanalysis generally had maxima in similar places. However, quantitatively, the CCSM3 had a mean CAPE bias toward regions of warm water throughout the European region. This is consistent with Marsh et al. (2007) who found a large mean CAPE bias toward the warm waters of the Gulf of Mexico and Gulf Stream Current. Because CAPE dominates the favorable severe environments calculation, large biases in mean CAPE tends toward large biases in favorable severe environments. This is the most likely reason why the CCSM3 favorable severe environments were also biased toward regions of warm water.

Comparisons of the CCSM3’s future simulation to the current simulation provided a first glimpse at the potential impact of anthropogenic climate change on the European severe thunderstorm environment. Generally, mean CAPE values decreased in the warm season and increased in the cool season. The joint distribution of CAPE and deep layer shear captured a decrease in low CAPE, higher deep layer shear environments and an increase in higher CAPE, lower deep layer shear environments. Even though the future simulation had a decrease in mean CAPE values in the warm season, the number of favorable severe periods increased in the warm season.

Based on the increase in the number of favorable severe periods it is tempting to claim that an increase in severe thunderstorms would be expected in a future characterized by anthropogenic warming. However, one drawback to using the favorable severe environment calculation is that it says nothing about whether or not an environment was sampled by a thunderstorm. This lack of information about thunderstorm initiation prevents one from making an unqualified claim about what will happen to the number of severe thunderstorms. At best, one can say that the CCSM3 predicts the number of favorable severe environments will increase in a future characterized by anthropogenic warming.

A potential explanation of the lack of mean CAPE over mainland Europe might be found in the CCSM3’s deep convection parameterization. The nature of this parameterization is to convect when sufficient amounts of CAPE have built up to penetrate any stable layer in the model. This convection destroys the pent up CAPE and affects the model’s precipitation field. This increase in precipitation would potentially affect the transport of low-level moisture downstream, which would impact the generation of CAPE. Hence, regions of CAPE sufficiently large to convect might rob areas downstream of low-level moisture and, in turn, CAPE. Because of the CCSM3’s warm water CAPE bias, it is possible that persistent convection might be occurring over regions of warm water preventing low-level moisture from being transported to mainland Europe.

Acknowledgements

The authors would like to thank the NCAR for archiving, storing, and making accessible the high resolution data from the CCSM3 and Luca Cinquini of Earth System Grid for help with accessing these data. The authors would also like to extend gratitude to Mary Haley of NCAR for access to and help in debugging several NCAR Command Language scripts necessary for computing the necessary CAPE fields. Additionally, gratitude is extended to Melissa Bukovsky for help with learn NCL and Ryan May for help with learning Python’s matplotlib module. Lastly, thanks must be given to M. O. Nkey for support during the writing of this paper.

This research was supported by NSF SGER grant ATM-0550178. David Karoly is supported by an Australian Research Council Federation Fellowship (project number FF0668679).

References


205


